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Functionally Tailored Multi-component Composite Structures via Additive Manufacturing

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2015 Seedling Phase II Technical Seminar
November 17 & 19, 2015

Outline

- Introduction
- The innovation
- Impact
- Technical approach
- Material Processing
- Mechanical Testing
- Results of the Seedling effort to date
- Distribution/Dissemination
- Next steps

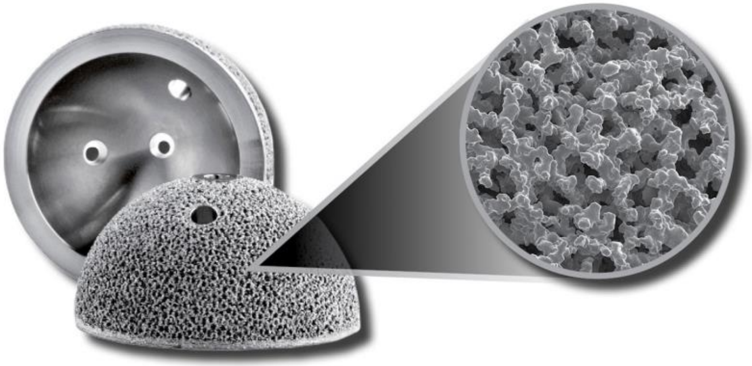
Team

- Craig A. Brice
  - Formerly NASA Langley; currently Lockheed Martin
- John A. ("Andy") Newman, Wesley A. Tayon, Joel Alexa, Jim Baughman, Pete Messick, Ravi Shenoy (retired), H.D. Claytor
  - NASA Langley (CS and contractors)
- Kenneth G. Cooper, Quincy A. Bean, Phillip Steele
  - NASA Marshall

Introduction

- Metallic foam structures
  - Open cell foams can be fabricated through established foaming processes for some alloys (e.g., Al, Cu, Zn)
  - Closed cell foams can be produced via powder metallurgy (e.g., Ti, Ni, Fe)
  - Additive manufacturing opens new possibilities for novel foam structures for a wide range of alloys
  - This project will use additive manufacturing to create open cell structures than can be infiltrated with other alloys to create bi-metallic composites

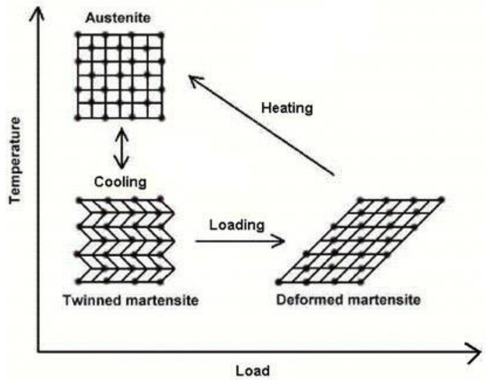
www.ergaerospace.com



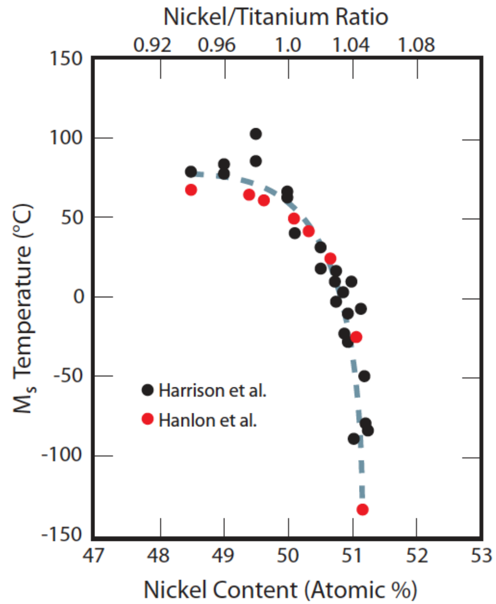
www.arcam.com

Introduction

- The shape memory effect is well documented and being studied for numerous applications
- Change in crystal structure from high temperature austenite phase to a low temperature martensite phase
- Plastic strain accommodated by twinning; recovered by reverse transformation (heat or strain)
- The objective is to exploit this phenomenon to produce beneficial residual stresses that inhibit crack growth



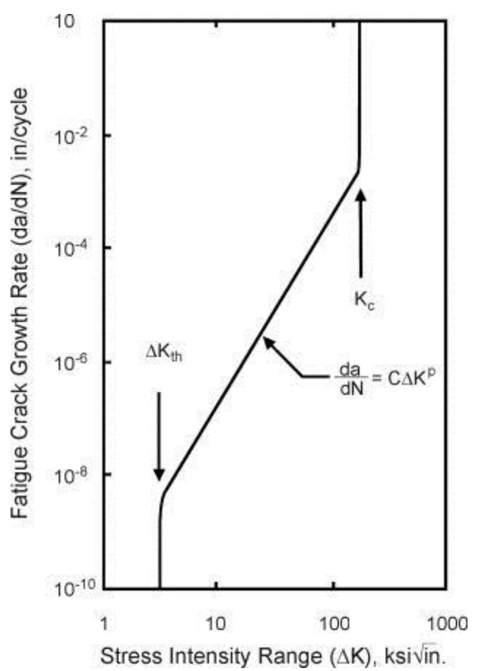
www.keytometals.com



www.asminternational.org

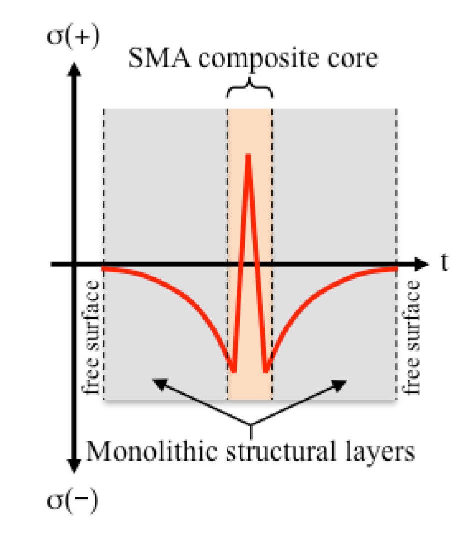
The Innovation

- Strain fields within a structure can have a significant impact on properties and performance
- Cracks tend to nucleate from a free surface and grow when stress levels exceed the threshold stress intensity factor (ΔK_{th})
- Below the threshold level cracks do not grow



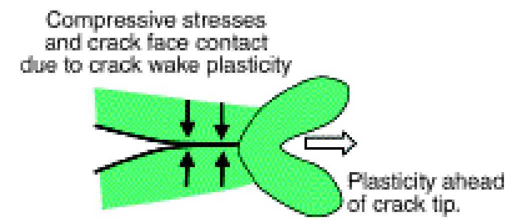
Handbook of Damage Tolerant Design

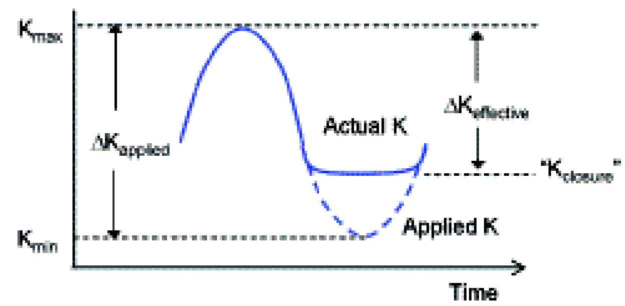
<u>Objective</u>:
Create a unique bi-metallic composite structure with a carefully designed residual stress field that can be tailored to limit or eliminate the ability of a surface crack to propagate through the structure.

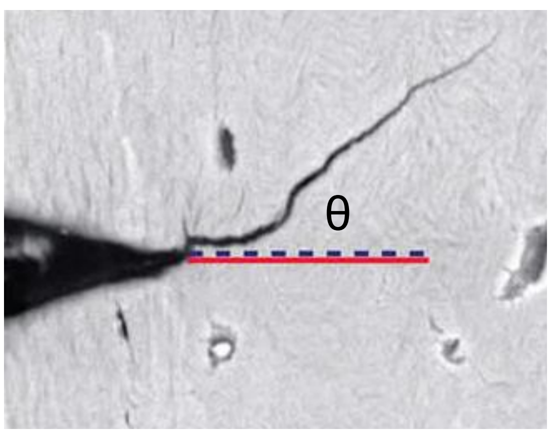


Affecting Crack Driving Force

- Crack closure
  - Compressive residual stress may promote premature clamping of crack faces reducing the effectiveness of cyclic loading
- Crack deflection
  - Residual stresses or diagonal reinforcements may cause crack deflection; deviation away from the plane of highest principal normal stress with decrease the crack-tip driving force
- Interfaces between dissimilar materials
  - Cracks may not readily grow between Ti-6Al-4V matrix and NiTi







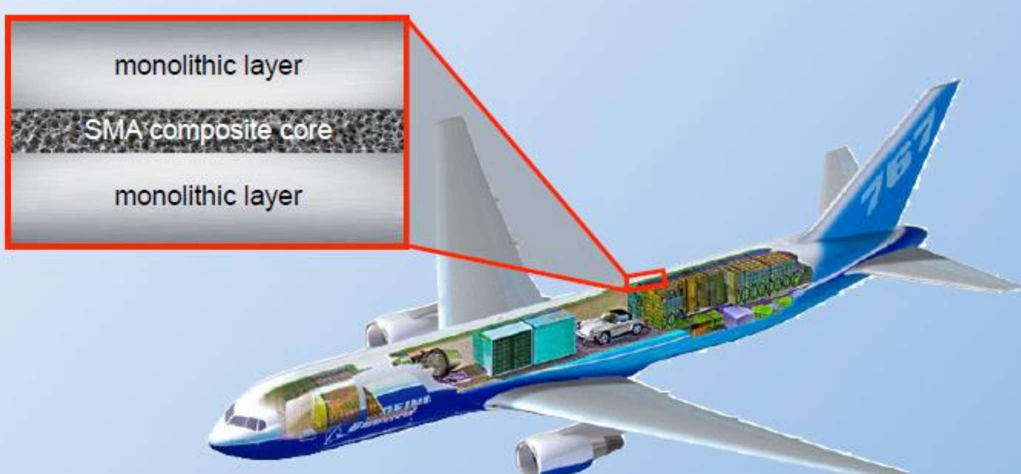
Impact

This concept could greatly impact the fatigue performance of aerospace components through crack closure and/or deflection

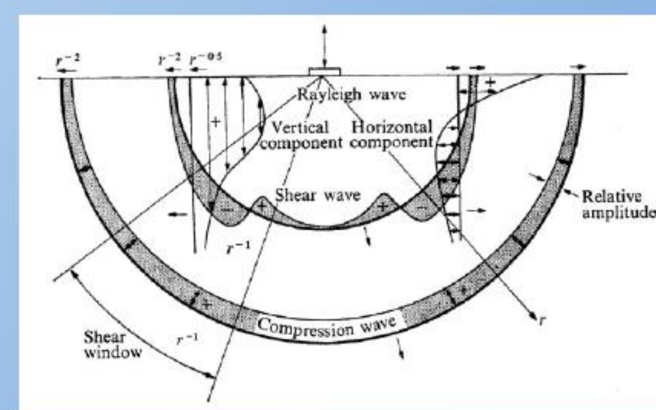
- Improved structural efficiency in damage tolerance limited applications

Potential use in anti-ballistic impact applications through shock wave disruption/attenuation

- Micrometeoroid and Orbital Debris (MMOD) shielding
- Armored tactical vehicles



www.boeing.com

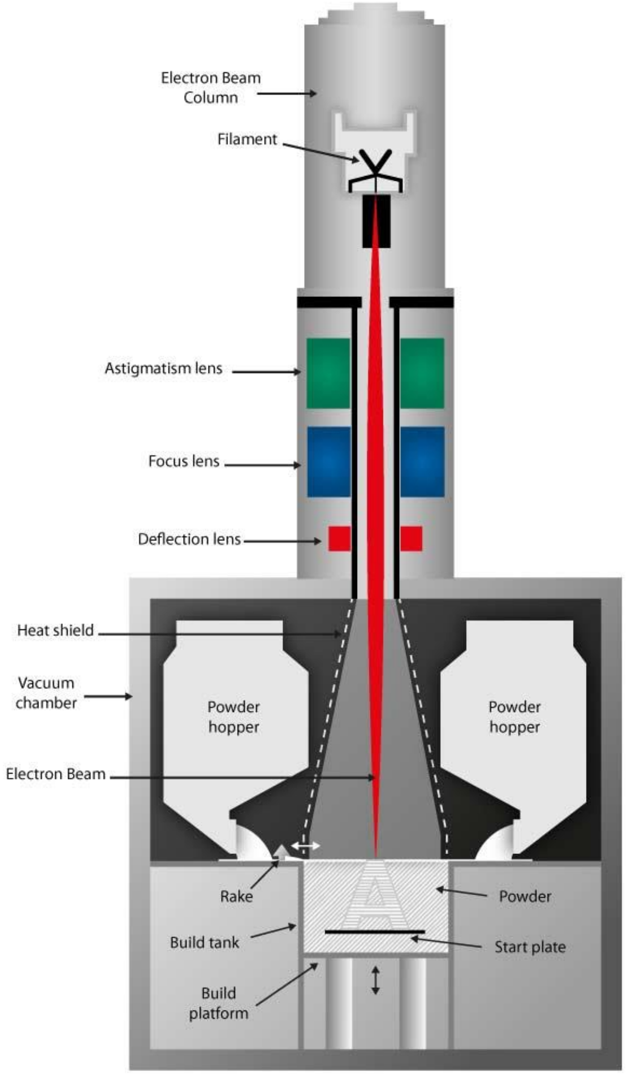


K.F. Graff, "Wave Motion in Elastic Solids", 1975 Clarendon Press, Oxford

Technical Approach – Processing

The Arcam electron beam powder bed additive manufacturing process was used

- Fabrication was done at U. of Texas at El Paso (phase I) and Marshal Space Flight Center (phase II)
- Thin layer of powder is spread over a substrate and fused together using electron beam
- Substrate platform increments downward and the process is repeated for another thin powder layer
- This process is repeated until the desired 3-D structure is created

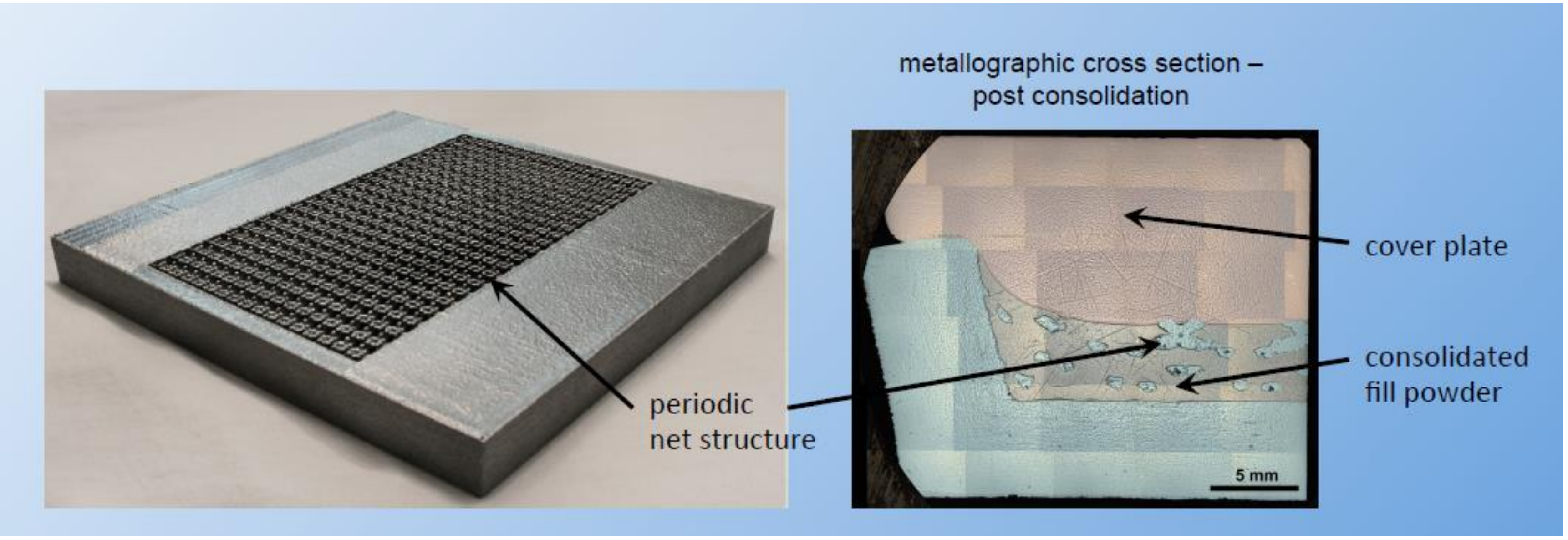


www.arcam.com

Technical Approach – Processing

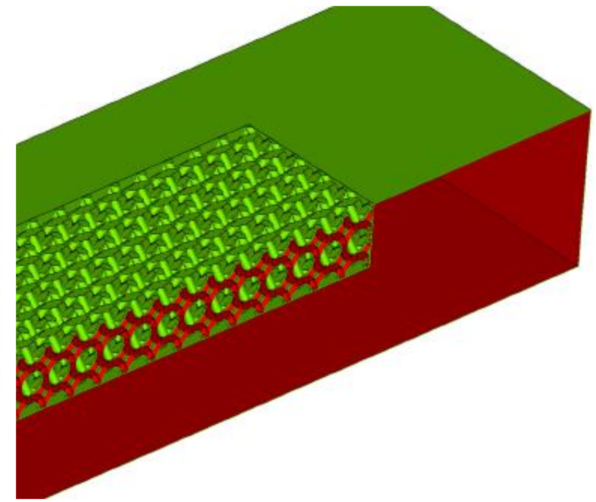
Utilize additive manufacturing to create open cell net structures to be infiltrated with a secondary alloy powder and hot consolidated into a fully-dense, multi-alloy material

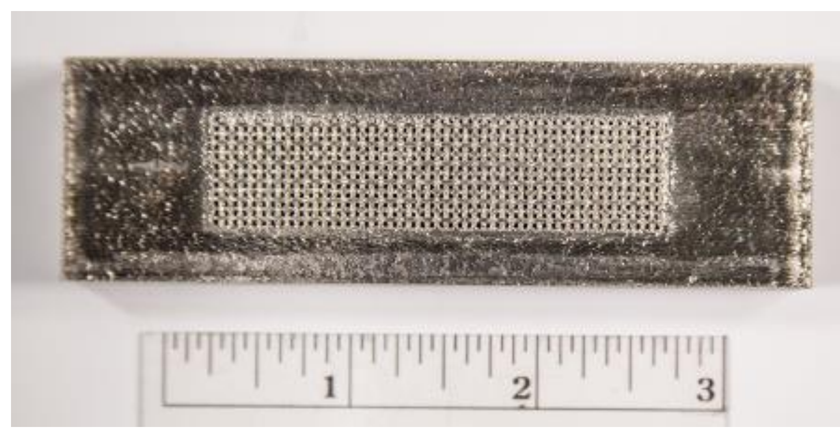
- Proof of concept with Ti-6Al-4V AM-fabricated material infiltrated with commercially-pure titanium and vacuum hot pressed to full density



Material Design

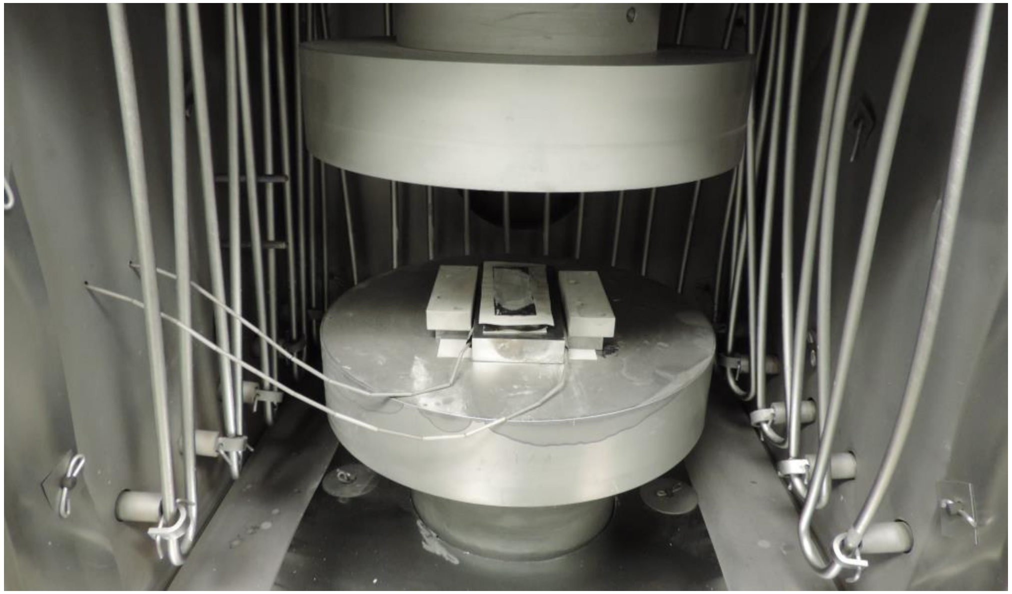
- Periodic cell structure
  - Diagonal crossing pattern
  - Approximately 1mm spacing between cell centers
- Arcam samples
  - Ti-6Al-4V
  - Nominal dimensions
    - 100mm by 31mm
    - 7mm border on sides
    - 19mm border on ends





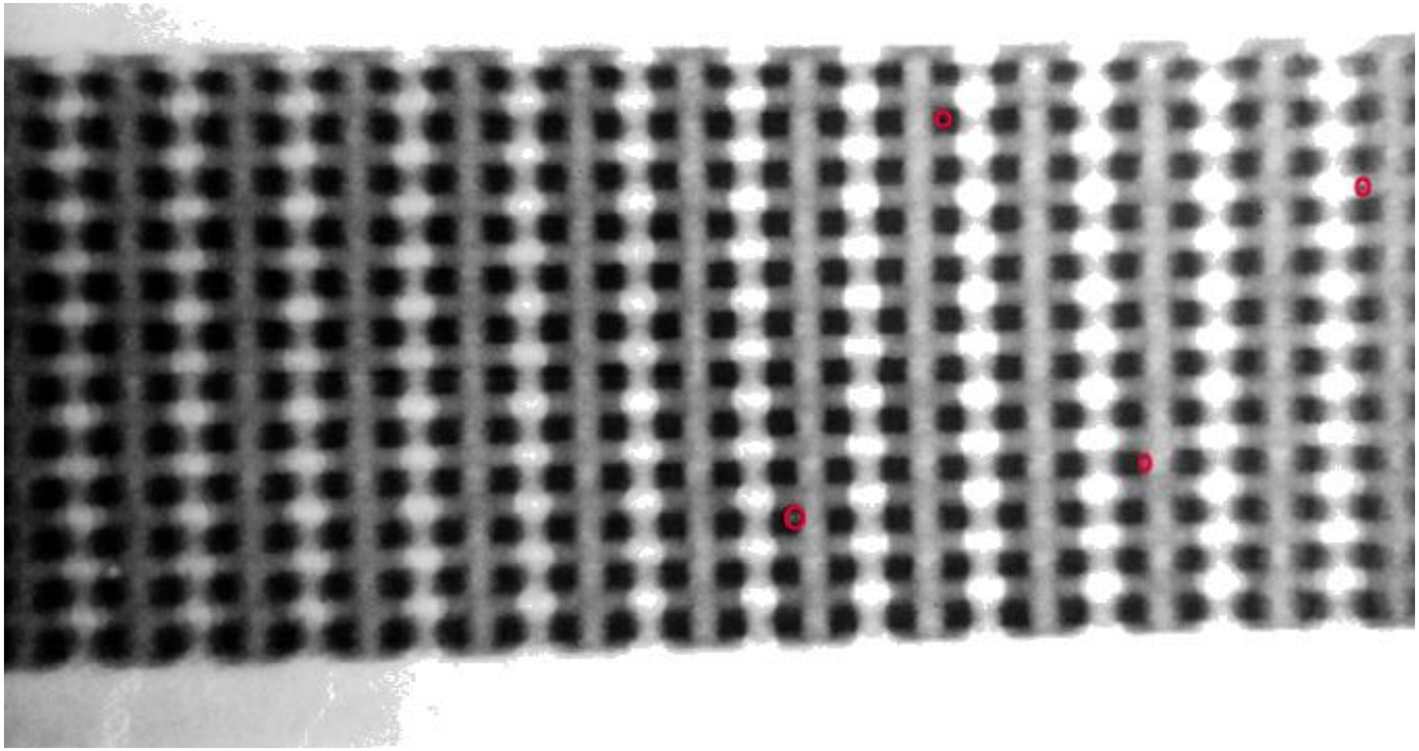
Material Processing

- Ni-Ti powder vibrated into open cell samples
  - 50.7 at% Ti; 49.3 at% Ni; -140 mesh (<105 μm)
  - $A_s = 68^oC$; $A_f = 109^oC$; $M_s = 78^oC$; $M_f = 38^oC$
- Mechanical die is used; material consolidation by hot pressing
  - 940^oC for 4 hours at 1,000 psi
- Perform shape set heat treatment
  - 500^oC for 15 minutes
- Cold rolling
  - 5% reduction in thickness
- Memory activation
  - 115^oC for 15 minutes



Material Processing

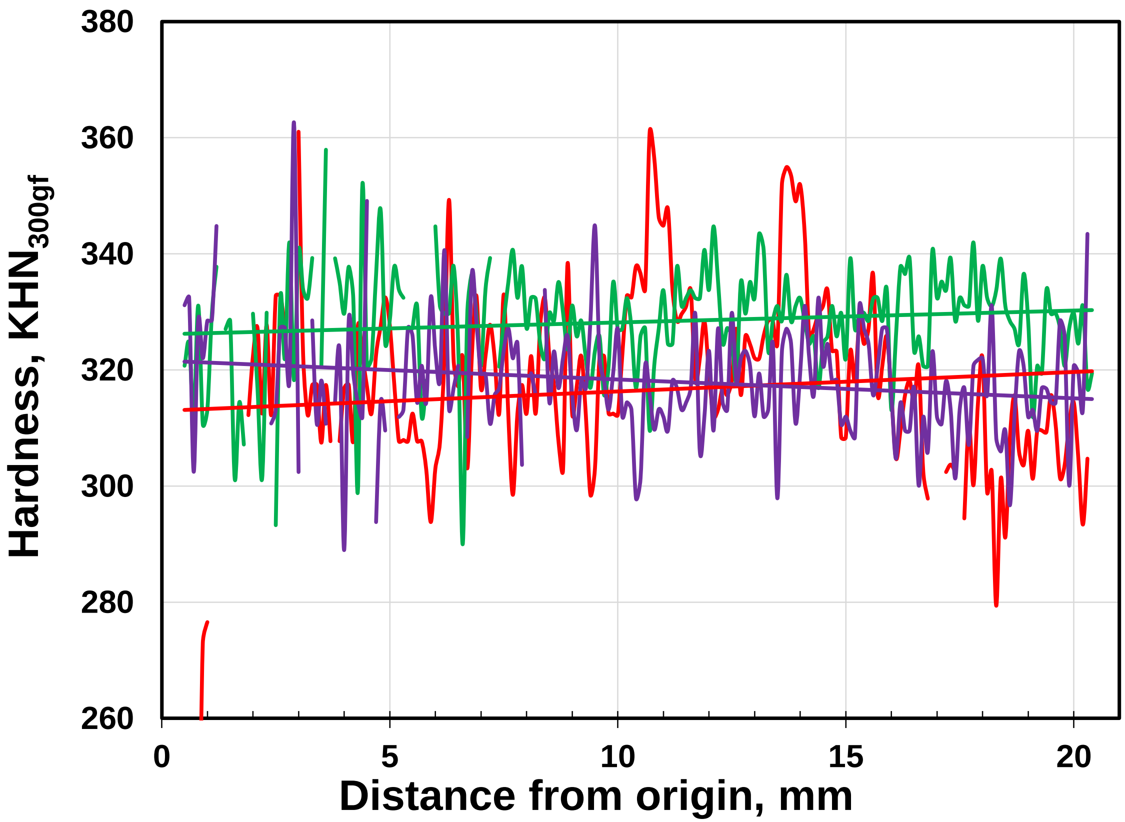
- Radiography of vacuum hot pressed sample performed
  - No major voids found indicating complete fill of open cells
  - Some incidental porosity found (red circles)

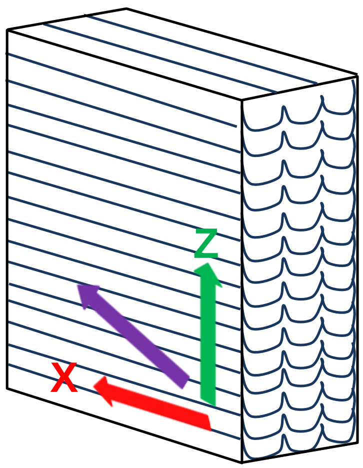


Hardness Test Results

Testing performed on X-Z plane with Knoop indenter aligned to:

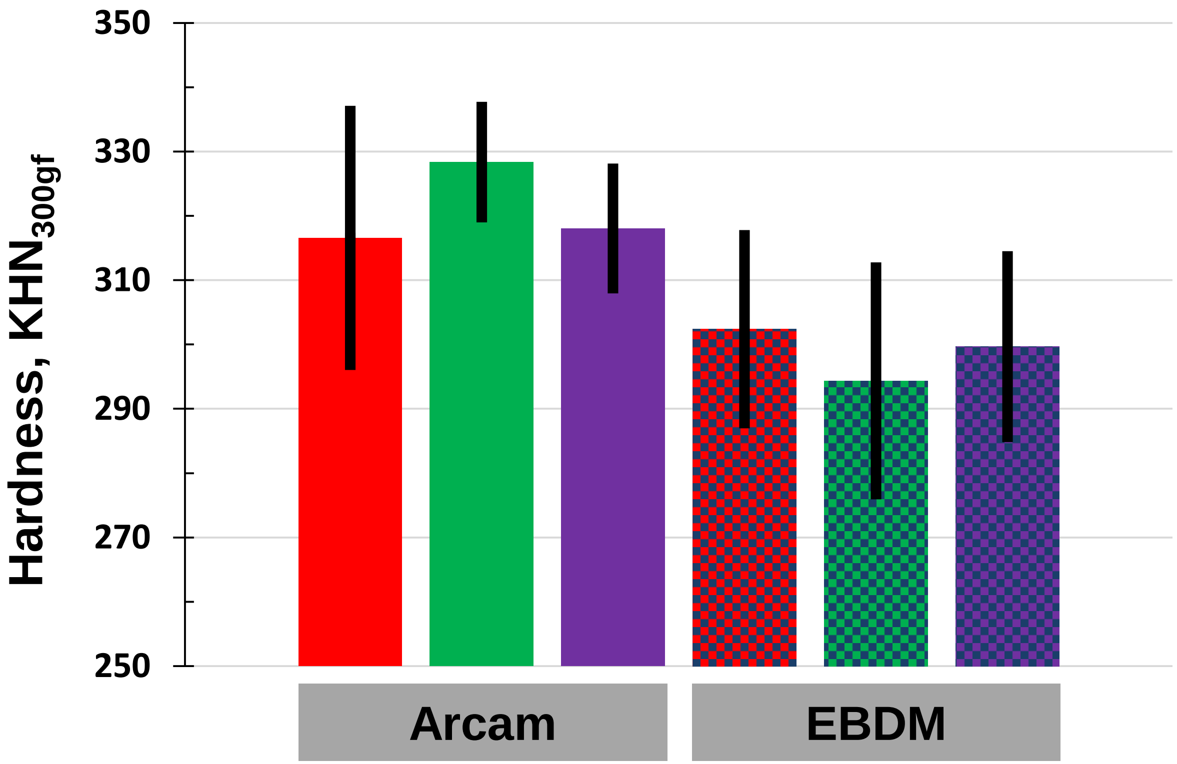
- Plane of deposition (X)
- Normal to deposition plane (Z)
- 45 degrees in-between





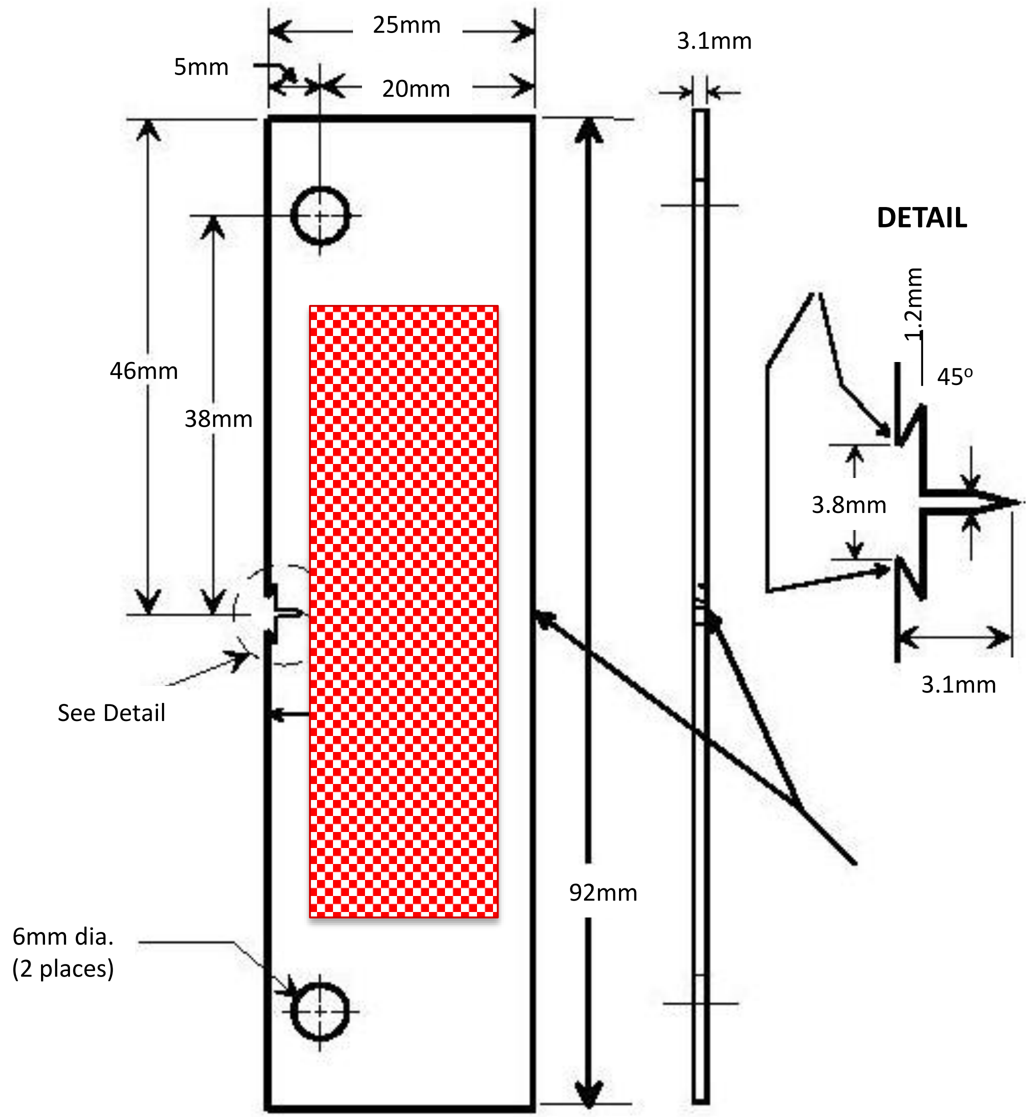
Hardness Test Results

Hardness of Arcam product is superior to other e-beam AM deposition method

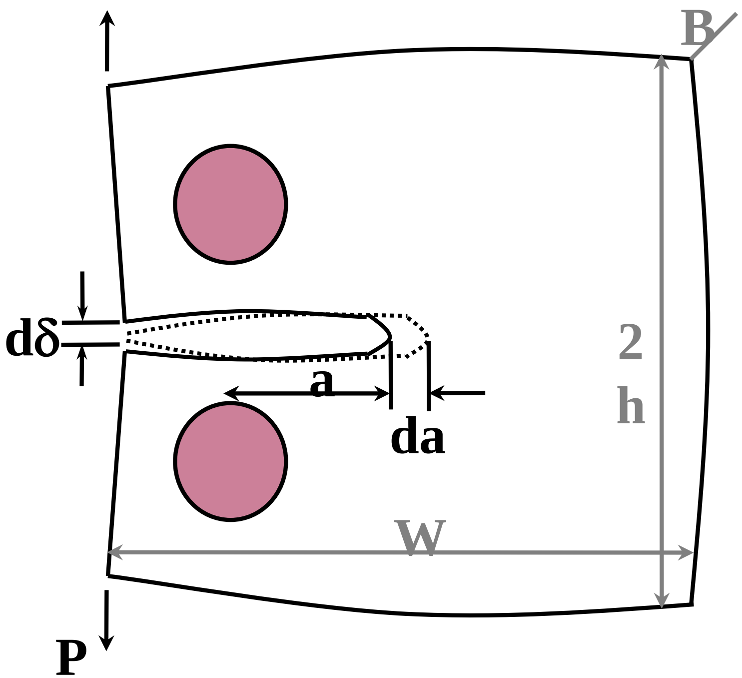


Fatigue Crack Growth Specimen

- Eccentrically-loaded single-edge notch tension (ESE(T)) specimen
  - Pin loaded
  - Tests run in K-control
    - Crack mouth opening used to monitor crack length during test
    - Automated system continuously adjusts load to achieve programmed crack-tip stress intensity factors (ΔK)
    - Residual stress component of crack-tip stress intensity monitored by tracking zero-load offset of crack mouth opening (similar to cut-compliance test)



Residual Stress Determination



$$K_{res} = \frac{E}{Z(a)} \cdot \frac{d\delta}{da}$$

Z (*a*) = influence function

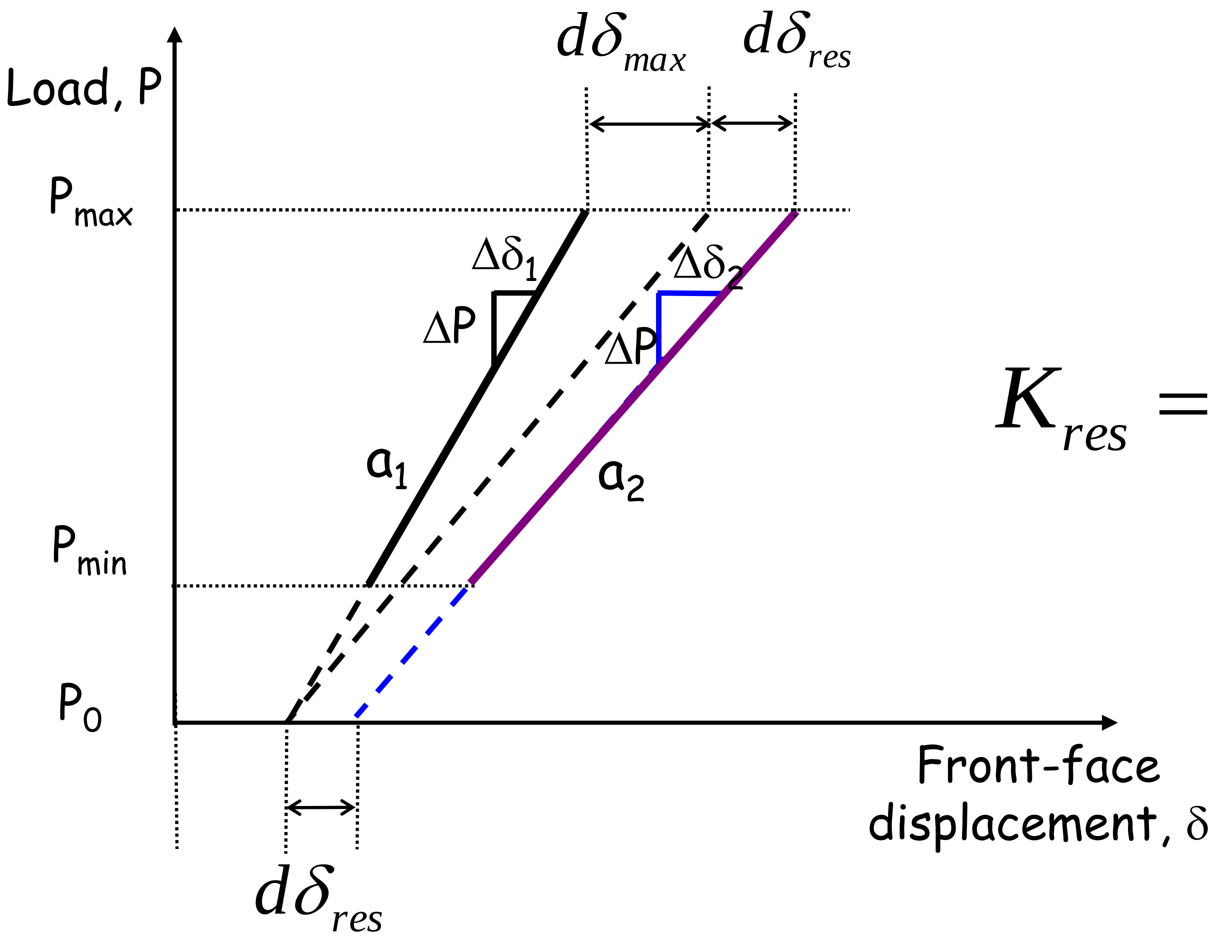
$$Z(a) = \frac{4 \cdot (2W + a) \cdot F_2\left(a/W, h/W \right)}{(W - a)^{3/2}}$$

- Measure changes in notch displacement for incremental changes in crack length ⇨ K_{res} can be calculated
- *Z(a)* depends on size, geometry, strain measurement location, but not on the residual stress distribution

References

- H.-J. Schindler, W. Cheng, and I. Finnie, *Exp. Mech.* **37**, 272–277, 1997.
- M. B. Prime, *Fatigue & Fracture of Engineering Materials & Structures*, **22**, 195-204, 1999.
- X. R. Wu and A. J. Carlsson, 1991.
- Diana Lados, 2006
- M. B. Prime and M. R. Hill, 2002

Residual Stress Determination

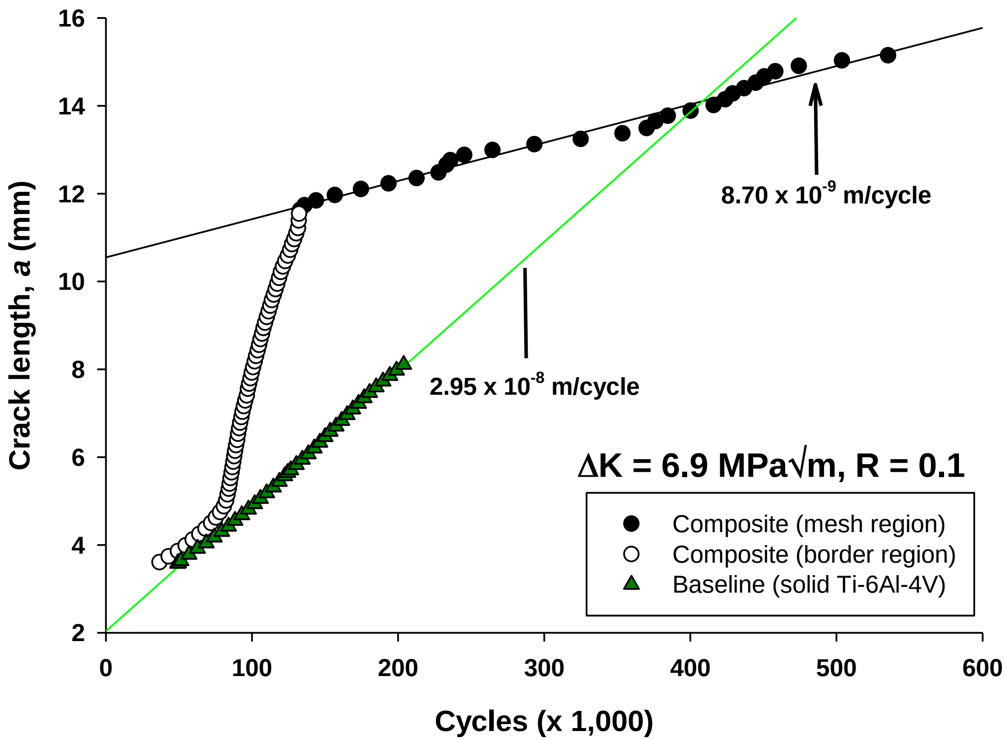


$$K_{res} = K_{max} \cdot \frac{d\delta_{res}}{d\delta_{max}}$$

Reference: K. Donald, FTA.

Fatigue Crack Growth Testing

- Constant-ΔK test
  - Slope of plotted data is crack growth rate (d*a*/dN)



- Baseline test (solid Arcam product)
  - Steady d*a*/dN
  - Little residual stress detected
- Composite test
  - Initially same rate as baseline
  - d*a*/dN increased with tensile residual stress
  - d*a*/dN abruptly decreased as crack grew into NiTi mesh region
    - Highly-unsteady, but compressive residual stress

Results to Date/Summary

- Material produced
  - Well-consolidated, nearly-fully-dense metallic composite
- Material characterized
  - Small pores, but otherwise well consolidated
  - No delaminations or imperfections observed at Ti-6Al-4V/NiTi interfaces
- Material tested
  - Bi-metallic composite in a state of prestress (residual stress); slight material warping observed
  - Fatigue crack growth testing revealed that suppression of crack growth rates occurred in the NiTi-rich region of the specimen corresponding to compressive residual stresses

Dissemination

- C.A. Brice, W. Tayon, J.A. Newman, R.N. Shenoy, S. Sankaran, S. Gardner, and Z. Loftus, "Characterization of Titanium Alloys Fabricated by Additive Manufacturing," presented at the 13th World Conference on Titanium, August 19, 2015, San Diego, California.
- C.A. Brice, "Bi-metallic Composite Structures with Designed Internal Residual Stress Field," NASA/TM-2014-218174.
- J.A. Newman, C.A. Brice, W.A. Tayon, and K. Cooper, "Functionally Tailored Multi-component Composite Structures via Additive Manufacturing," in progress; to be submitted as a NASA/TM.

Next Steps

- Characterization of residual strain field
  - Mechanical test results suggests variation in residual stress occurs on small length scale
  - Digital image correlation should be used to characterize the residual strain field on the specimen surface
    - Strain field determined by tracking relative displacements of speckles on specimen surface during mechanical testing
    - Could characterize shape-memory transformation in NiTi and crack closure
    - Able to use image correlation on a wide range of length scales (from mm to nm)
- Fatigue testing could provide additional information
  - Cyclic loading but with no crack
  - Cracks would naturally initiate, likely at regions of tensile residual stress
  - Equilibrium requires there to be regions of tensile residual stress to offset regions of compressive residual stress